

5 Environmental Impacts of Micro Cogeneration

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During the past decades, many efforts have been made to improve the environmental performance of energy conversion systems. One of the most prominent examples is the reduction of sulfur dioxide emissions through flue gas desulfurization. Other environmental impacts have also been reduced in the course of implementing modern power plant technologies, power plant modernization or restructuring, and switching fuels.

Nevertheless, the increasing demand for services, mobility, light, communication, and heating is still responsible for significant environmentally damaging effects, which are caused throughout the whole energy conversion life-cycle: from primary fuel extraction, through processing, distribution and conversion into electricity or heat, to energy delivery and use. The related impacts, such as oil tanker spills, the accumulation of radioactive waste, the emission of hazardous substances, and the use of non-renewable energy resources, continue to damage our environment.

Among the most challenging issues today is the anthropogenic emission of greenhouse gases. The scientific community acknowledges that far-reaching measures have to be taken to reduce the increase in CO₂ concentration in the atmosphere, in particular with regard to energy use. However, even the unambitious goals of the Kyoto protocol for the reduction of greenhouse gas emissions will not be met by many countries worldwide.

It has often been argued that, due to its decentralized nature and high total efficiencies, cogeneration, and ultimately also micro cogeneration, contributes toward environmental relief. The present chapter evaluates this assumption and investigates the potential environmental effects of a diffusion of micro cogeneration on the following levels:

1. Foremost, the direct impacts of power plant *operation*. This concerns, for example, the emission of pollutants or climate-altering gases –

¹ CF: Section 5.3.3

which depends significantly on the efficiency of fuel conversion –, the use of lubricants or other auxiliary materials and the like.

2. The upstream environmental impacts of *fuel supply*, e.g. the extraction, processing, and transport of gas or other fuels required for the operation of the system. In cases where micro cogeneration systems have lower fuel demand than competing technologies, the upstream impacts may be smaller as well.
3. The environmental impacts of *power plant manufacturing and construction*. Typically, due to the long life span of the systems, power plant production is of lower importance than the other life cycle stages, unless some very environmentally detrimental materials are used (Pehnt 2002).
4. The impacts of electricity and heat *distribution*. The transport of electricity (in electricity grids) and of heat (e.g. in district heating systems) inevitably leads to loss (see Sect. 5.3.1), which can be partially avoided through local production of electricity.
5. *Connecting* micro cogeneration plants to “virtual power plants” by means of communication devices. This could either create further environmental impacts or reduce them.
6. *Indirect environmental impacts*, which could be created due to the immediate influence of decentralized systems on customer behavior.

5.1 Life Cycle Assessment of Micro Cogeneration

To assess the issues raised in items 1 through 4 for the case of micro cogeneration, and to compare it to competing energy supply technologies, we use the methodology of *life cycle assessment* (LCA). The two key elements of LCA are

- assessment of the total life-cycle (“cradle-to-grave approach”) of a given energy conversion technology, including the exploration, processing, transport of materials and fuels, the production and operation of the investigated energy conversion units, and their disposal/recycling, and
- assessment of different environmental impacts on resources, human health, and ecosystems.

An LCA basically consists of four steps: firstly, a *goal and scope definition* serves to describe the investigated product, the data sources and system boundaries, while defining the functional unit, i.e. the reference for all related in- and outputs. This functional unit could be, for instance, the

provision of one kilowatt-hour electricity to the customer or the supply of a hotel with heat and electricity for one year. Secondly, an *inventory analysis* “involves a data collection and calculation procedure to quantify relevant inputs and outputs” (ISO 1997). Thirdly, the potential impacts of the in- and outputs of the inventory analysis are determined by an *impact assessment*, which categorizes and aggregates the environmental interventions. For that purpose, impact categories, such as global warming, eutrophication, acidification, or summer smog are defined and characterization factors calculated which describe the contribution of different substances to that particular impact category (e.g. CO₂, CH₄ or N₂O to global warming). Fourthly, through *interpretation*, the findings from the inventory analysis and the impact assessment are combined in order to draw conclusions or formulate recommendations.

In the case of micro cogeneration, specific issues are associated with data uncertainty and forecasting, because many of these technologies are not yet fully developed (Pehnt 2003). In addition, cogeneration is a technology path with joint or co-products, which have to be taken into account to obtain a full picture of the environmental consequences.

5.1.1 Considering the Co-product

For the results of an LCA of cogeneration systems, the way that the co-product is considered turns out to be important. As cogeneration systems produce heat and electricity simultaneously, and the comparison to other, non-cogeneration systems often takes place based on the functional unit “1 kWh electricity” or “1 kWh heat”, both products need to be taken into account together.

This situation is very similar to that which many companies have to deal with when they have more than one product to sell. Take for instance a farmer raising cows. Each cow produces milk; but eventually it will be slaughtered and converted into meat. How can the farmer allocate the cost of feeding a cow to produce both milk (daily) and meat (at the end of the cow’s life)?

There are two main ways to deal with this problem. The first is *allocation* of the cost between the products with an appropriate key. In the case of the farmer, this might be the relative nutritional value of milk and meat, or the prices of milk and meat on the market.

For the case of a cogeneration system, one allocation key could be the energy generated. Take the example of an electric efficiency of 40 % and a thermal efficiency of 40 %. For each kWh electricity, one kWh heat is produced. The allocation key would thus be 50:50. That means that 50 %

of the CO₂ emissions are related to the production of electricity and 50 % to heat.

However, this allocation key does not really characterize the value of the products. Instinctively, one kWh electricity seems more valuable than one kWh low-temperature heat. And, in fact, only a fraction of the heat could be converted into electricity. Therefore, often the *exergy* is used as the allocation basis. Exergy describes the amount of useful energy that is contained within a product. The exergy of electricity is equivalent to its energy, whereas the exergy of heat, in contrast, is given by the Carnot efficiency multiplied by the energy value.

The second way to deal with co-products is to estimate the *avoided burden*. If a cow, for instance, had not produced milk, it would have been necessary to buy some substitute, such as soy milk. The total cost for its meat would then be the sum of feed costs over the lifetime of the cow minus the avoided costs for soy milk.

In the case of a micro cogeneration system, this means that – if we want to compare micro cogeneration to other electrical power plants – we have to identify the heating systems that would actually be replaced by such systems. This depends on a number of factors, for instance the country, the type and age of the houses, the preferred fuels, and the like. It also depends on the perspective of the decision-maker: from the perspective of a home owner who installs a new system, it is the individual, old heating system that might be superseded by a micro cogeneration system. Boiler manufacturers might think of micro cogeneration competing with other modern heating systems. A politician who has to decide which heating system to support financially will have to consider, for instance, a micro cogeneration home energy system compared to a modern condensing boiler.

For the cogeneration systems investigated here, we choose the *avoided burden approach*, where the co-product is credited with an alternative generation route. This approach reflects most accurately real decision-making situations. Also, if we had chosen an allocation procedure, it would be necessary to compare micro cogeneration to other electricity *and* heat systems simultaneously.

We furthermore regard electricity as the main product, while generated heat is credited, and analyze the replacement of a gas condensing boiler by a variety of micro cogeneration systems. The question answered through this substitution perspective is: which environmental impacts do micro cogeneration systems have if we install them instead of a modern gas condensing boiler? Choosing this perspective relies on the following assumptions:

- **Fuel.** We want to determine the effects of a new technology, not of switching fuels. For instance, switching from oil to gas offers environmental advantages. However, this fuel switch can also be accomplished with other technologies. It cannot be causally attributed to micro cogeneration. Therefore, we assume the same fuel for the substituted heat supplying technology.
- **Marginal systems.** Usually, micro cogeneration will not be installed as a substitute for an older technology. It will rather be viewed as an alternative to another modern technology when replacement is required in order to meet future demands for heat and electricity. In this sense, two modern, marginal systems are to be considered as substitutes. Hence, for investors, households, or decision makers, the relevant question is: which technology is to be preferred from an environmental perspective?

Combining these two assumptions, a modern gas condensing boiler is considered as the substituted heat technology. It should be kept in mind that this way of crediting is the most conservative way to assess micro cogeneration. The advantages of micro cogeneration, compared to central generation without it, increase significantly as soon as less modern technologies or fuels with higher carbon contents are considered as the substituted heat supply.

Which *electricity* system should the micro cogeneration systems be compared to? Again, this depends on the perspective of the decision maker. To identify advantages and disadvantages in comparison to the status quo, the current electricity mix can be chosen as a benchmark. Generally, however, we need to take a dynamic, forward-looking perspective. In Germany, for instance, some 40 GW_{el} power plant capacity must be replaced by 2020 (see Chap. 2). Micro cogeneration represents one alternative way to cover this demand for new capacity. Micro cogeneration should, therefore, be compared to modern marginal power plants that would typically be installed. In many cases, this will be a natural gas power plant. This procedure is in accordance with the EU directive on cogeneration, which demands that

each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit (EU 2004).

On the other hand, the generation characteristics of micro cogeneration systems tend to contribute to peak load as well. The peak load power mix differs from country to country. In Germany, for instance, it includes low

efficiency gas power plants, but also virtually CO₂ free hydropower plants. In our environmental comparison, we include both mix and gas combined-cycle plants to represent the alternative paths for centralized electricity generation.

5.1.2 Input Data for Micro Cogeneration Systems, Fuels, and Conventional Power Plants

The micro cogeneration systems investigated have already been defined, as summarized in Table 4.1, and include several fuel cell, Stirling, and reciprocating engine configurations. These are compared to larger cogeneration systems, such as a large reciprocating engine and a gas combined-cycle plant both feeding district heating systems. As benchmarks for separate generation options, a gas combined-cycle plant without cogeneration, a modern lignite power plant, and the future German electricity mix, as forecasted by Enquête (2002), are assessed.

The reference time of the comparison is the year 2010. We choose this base year because several of the micro cogeneration systems, namely the fuel cell, the very small reciprocating engine, and the Stirling engine, are not yet fully technologically mature. For these systems, we do not evaluate the status quo, but rather extrapolate the technical performance to the year 2010, to take into account further expected technological progress.

We restrict our LCA analysis to natural gas and fuel-oil as fuel. Even though micro cogeneration can, in principle, be operated with other fuels (see Sect. 9.4 for a discussion on fuel flexibility), the greater part of the systems will be operated with natural gas. Furthermore, by 2010, renewable micro cogeneration systems, such as pellet Stirlings or biomass gasification/fuel cell units, are not yet likely to be mature. It is obvious, however, that with respect to greenhouse gas emissions, the use of renewable fuels would be preferable (see Sect. 5.2.2) .

For the purpose of our research project, life cycle data were obtained for various micro cogeneration and conventional systems from the system manufacturers and additional data sources. The LCA data were then implemented using the material flow and life cycle program Umberto (www.umberto.de). This program calculates the impacts caused by the full life cycle of the micro cogeneration systems and carries out an impact assessment in accordance with the international standard ISO 14042.

The fuel cell LCAs are based on our analysis in Krewitt et al. (2004). The materials LCAs used for the various technologies, such as catalyst materials (e.g. platinum group metals), building and structural materials (such as concrete and steel), and materials for the electrical equipment

(copper etc.) are mainly based on Pehnt (2002). The natural gas LCA, as modeled in Umberto, represents a standard import mix for Germany, extrapolated to the year 2010 (gas sources: Germany 13 %, Netherlands 19 %, Norway 33 %, GUS 35 %). Electricity and conventional heat production data are taken from the detailed bottom-up Umberto/IFEU database. The district heating systems are based on the detailed model described in Chap. 4, including heat losses depending on the heat density, the length and isolation of the distribution grid, etc.

To account for uncertainties regarding the actual course of future development, but also variations with respect to application, manufacturer, technology, and other parameters, error bars are used to show the bandwidth of results. Some of the important input parameters included in the bandwidth are discussed below with respect to representativeness and validity.

- *Thermal efficiencies* depend strongly on: the application context, e.g. on whether a condensing operation can be achieved; which return temperatures are possible; how many start/stop procedures are carried out; how many full load hours are possible, etc. In addition, it is important whether a condensor is applied to exploit the condensing heat of the exhaust gas. This can, in principle, be used in most micro cogeneration applications. Often, it is rather an economic than an environmental question whether this extra device is used or not. Condensing operations are included in the possible system designs investigated here (Table 5.1).
- The emission of NO_x particularly of reciprocating engines varies strongly, depending on the emission reduction concept used ($\lambda = 1$ or lean operation, see Sect. 1.2.1), manufacturer, operation mode (partial load operation, static or dynamic operation, etc.), age of the system, and maintenance interval. The latter two aspects are particularly important for reciprocating engines. The NO_x emissions of $\lambda = 1$ systems can vary by one order of magnitude, depending on whether the catalyst has been newly exchanged or not. Likewise, emissions are very sensitive towards the calibration of engine characteristics. Engines in lean operation typically show more stable, but somewhat higher, emission levels. For the small Stirling engine, e.g. the WhisperGen, higher NO_x emission factors are reported. However, it is assumed that future systems will show reduced emissions, comparable to conventional gas burners.
- There is still uncertainty with respect to the bandwidth of unburnt methane (CH_4) emissions from reciprocating engines. In the literature on engine CHP, emission factors from 20 to 500 mg per MJ fuel input can be found. A Danish study, for instance, states that “compared to

complete combustion, the global warming potential for gas engines was on average raised by 20 % by the emission of unburned fuel” (Kristensen et al. 2004). Due to the high global warming potential of CH₄ (the impact of one kg CH₄ corresponds to 23 kg CO₂), 500 mg methane per MJ fuel corresponds to some 150 g of CO₂ equivalent per kWh electricity produced; methane emissions thus have a significant impact on overall emissions. Here, we assume a bandwidth of 10 to 320 mg/MJ fuel input, with 100 mg/MJ as default value based on field tests of reciprocating engines (Senertec 1992-2003). For fuel cells and Stirling engines, the emission factors are orders of magnitude lower.

- The condensing boiler as an “avoided burden system” is assumed to have an average efficiency of 97 %. This figure, indicating the somewhat low efficiency of the condensing boiler, was based on a large number of systems investigated in a variety of studies. It has been shown that the potentially high efficiency obtainable from the condensing operation cannot always be achieved, particularly in the summer.

Table 5.1. Input data for the LCA of micro cogeneration systems (see Table 4.1)

	Micro CHP										Larger CHP		
	Reciprocating engines						Stirling engines			Fuel cells		Recipr. engine	Comb. Cycle w/CHP
Reference number	1	2	3	3a	4	5	6	7	8	9	10	11	12
	1kW	3-6 kW (=1)	3-6 kW lean (HighNOX)	3-6 kW lean (Fuel oil)	3-6 kW lean (HighNOX cond)	3-6 kW lean (LowNOX)	0.8 kW	3 kW	9.5 kW	PEMFC	SOFC	50 kW	
Capacity (Default)													
Electric kW _{el}	1,0	4,7	5,5	5,3	5,5	5,0	0,8	3,0	9,5	4,7	1,0	50,0	
Thermal kW	3,25	12,5	13,9	11,4	14,9	12,6	6,0	15,0	28,5	12,5	2,7	98	
Efficiency (Default)													
Electric -	20%	25%	25%	28%	25%	25%	10%	15%	24%	32%	32%	30%	45%
Total -	85%	88%	88%	88%	93%	88%	85%	90%	96%	85%	85% *	88% **	88% **
Efficiency (min)													
Electric -	20%	25%	25%		25%	25%	10%	15%	22%	28%	28%	28%	45%
Total -	80%	84%	84%		88%	84%	80%	85%	88%	80%	80% *	85% **	80% **
Efficiency (max)													
Electric -	20%	25%	25%		25%	25%	12%	19%	26%	32%	32%	33%	49%
Total -	85%	95%	95%		99%	95%	90%	94%	100%	90%	90% *	90% **	88% **
NO _x emission													
Default mg/Nm ³	n.a.	125	300	2150	300	135	80	80	80	3	3	125	95
Bandwidth mg/Nm ³	n.a.	50-400	70-400	n.a.	70-400	60-200	-	20-110	20-110	-	-	50-400	n. a.
Economic Lifetime	80,000 hours or 15 years, whichever is lower												
All efficiencies are seasonal. * plus hot stand-by loss ** plus distribution losses													

All efficiencies are seasonal. * plus hot stand-by loss ** plus distribution losses

Lean = lean operation, cond = use of condensor

5.1.3 Impact Assessment

For an impact assessment, characterization factors are required so as to be able to calculate environmental interventions (such as greenhouse gas emissions or acidification) from emission factors. For this study, we take characterization factors in accord with standard LCA procedures (CML et al. 1992; UBA 1995; Franke and Vogt 2000; Giegrich and Detzel 2000). Due to space limitations, we can only present results for two important selected impact categories in this book: the emission of greenhouse gases (GHG) and acidification. The first category represents climate change effects, but also reflects the use of fossil resources, as the impact category is dominated by CO₂ emissions from fossil fuel use. The second assesses the contribution of local emissions of, for instance, NO_x, NH₃ and SO₂ to acidification. Structurally similar results could have been obtained for eutrophication, for example. A number of additional impact categories are included in the model but will not be reported here.

The results of these cradle-to-grave analyses will be described in the following sections. First of all, the contribution of micro cogeneration to climate change will be assessed (Sect. 5.2.1). Then emissions of pollutants are discussed in Sect. 5.2.2, followed by an assessment of immissions (5.2.3), and ending with a comparison on the household level of individual operators of micro cogeneration (Sect. 5.2.4).

5.2 Results of the Life Cycle Assessment

5.2.1 Greenhouse Gas Emission Reduction of Natural Gas Micro Cogeneration

Micro cogeneration versus central electricity production. As far as the prevention of GHG emissions is concerned, micro cogeneration systems are superior not only to the average electricity supply mix in Germany, but also to efficient and state-of-the art separate production of electricity in gas operated power plants and heat in condensing boilers (Fig. 5.1). Compared to separate generation with a natural gas combined cycle plant (without cogeneration) and a natural gas condensing boiler, micro cogeneration reduces GHG emissions by between 10 to 30 %, with the exception of the small Stirling engine. With lower electrical efficiency, its GHG level lies above the one of a gas combined cycle plant. Similar reductions are achievable with respect to primary energy demand.

There is still some uncertainty about the achievable total average efficiency of fuel cell systems. Estimates for future domestic systems range between 80 and 90 %, whereas today the systems are far from this value. When taking the lower bound of 80 % total efficiency for fuel cells only, the achievable reduction for domestic fuel cell systems does not seem very high. However, one can also reverse the argument: based on natural gas as a fuel, domestic systems might reach the same CO₂ emissions as a modern gas combined cycle plant, even though the systems are a factor of 100,000 smaller.

The reduction effects become greater when other fuels enter the comparison (see Sect. 5.2.2). For instance, compared to separate production with more coal-dominated electricity mixes, such as the German electricity mix, or even compared to a lignite power plant, GHG reductions above 50 % can be achieved. Also, comparison with oil-fuelled boilers would lead to even higher GHG reductions. In such cases, the GHG reduction is to a great extent due to a fuel switch from higher carbon-containing fuels to natural gas.

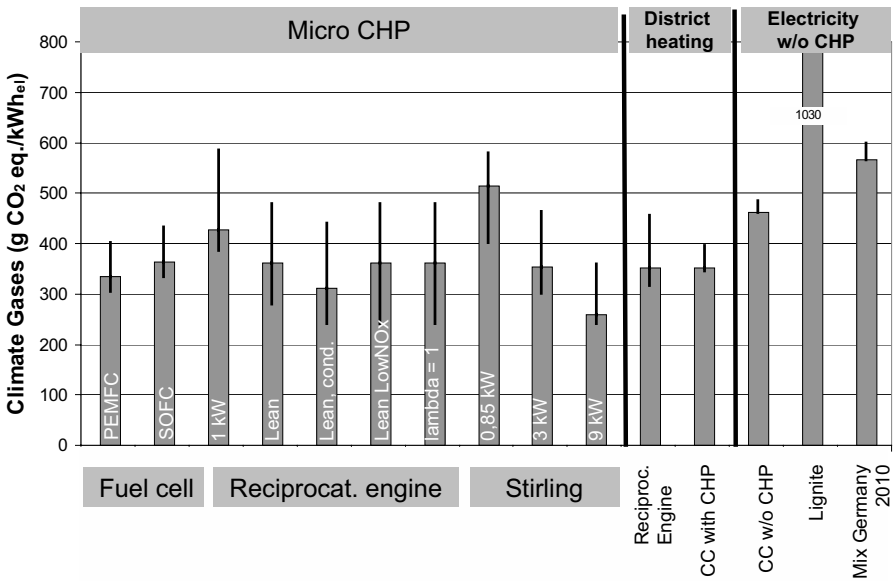


Fig. 5.1. Life cycle GHG emissions of micro cogeneration technologies compared to large CHP and conventional electricity production in the year 2010; Functional unit 1 kWh electricity at low voltage level, co-produced heat is credited (“avoided burden”; see Sect. 5.1.1)

Which is the best micro cogeneration technology? The determination of the best among the micro cogeneration technologies depends considerably on the efficiencies achieved. Under the assumption that gas condensing boilers are being substituted for, all technologies (fuel cells, reciprocating and Stirling engines) are within a very narrow range, with the exception of the small Stirling engine, which has lower electrical and overall efficiency. The high total efficiency of the large Stirling engine leads to the lowest GHG emissions. Fuel cells reach almost the same GHG emission level as the large Stirling when they achieve a total conversion efficiency of 90 %. However, their thermal management is more complex, and the heat sources inside the fuel cell system are diffused. This makes it more difficult to harvest the heat co-produced in the system than, for instance, in a Stirling or reciprocating engine.

Fig. 5.1 also unveils large variations in GHG emissions for each system. These are particularly caused by varying thermal efficiencies, which depend on a system's context (e.g. return temperatures) and configuration. In addition, for reciprocating engines, the values for methane emissions due to unburned natural gas vary considerably (see Sect. 5.1.2). Therefore, the error bar for this technology is larger. Further research and measurements are needed in this area.

Small versus large CHP. The comparison between the different sizes of CHP reveal that micro cogeneration leads to GHG emissions on a level similar to district heat cogeneration. Whereas the electrical efficiencies of large plants are generally higher than those of smaller units (Fig. 1.3), the total efficiency of large plants is not in general higher than that of the small systems. In addition, heat distribution losses for the district heating systems and electricity distribution losses in the case of large combined-cycle (CC) plants have to be taken into account. Whether large or small CHP is favorable, therefore, depends on the specific situation under investigation.

In any case, district heating systems are not only an efficient way of realizing CHP, but also offer the possibility of a straightforward integration of renewable energy carriers, such as biomass or solar thermal energy, into the heat supply (see Chap. 9).

Table 5.2. Reduction of greenhouse gas (GHG) emissions per kWh_{el} produced, achieved by micro cogeneration technologies with different baselines and heat credits; shown are the values for the default cases in Table 5.1; fuel: natural gas

Technology Status 2010		GHG reduction (heat credit: cond. boiler) compared to		
		Comb. Cycle w/o CHP	Mix G 2010	Lignite
Fuel cell	PEMFC	27%	41%	67%
	SOFC	21%	36%	65%
Reciprocating engine	1 kW	8%	25%	59%
	lean	22%	36%	65%
	lean, condensor	33%	45%	70%
	lean, LowNO _x	22%	36%	65%
	lamda=1	22%	36%	65%
Stirling engine	0.85 kW	-11%	9%	50%
	3 kW	23%	37%	65%
	9 kW	44%	54%	75%

Example: Production of electricity in a SOFC produces 36 % less GHG emissions than the future German electricity mix when we assume that a gas condensing boiler is replaced.

5.2.2 Pollutant Emissions

It is not only climate change that is an issue of current environmental policy efforts. More generally, the protection of human health and the environment is in focus. In Europe, Directive 2001/81/EC on national emission ceilings for certain atmospheric pollutants, the so-called NEC directive, controls the reduction of sulfur dioxide (SO₂), nitrogen oxides (NO_x), volatile organic compounds, and ammonia (NH₃). The aim is to combat impacts such as acidification, eutrophication, and ground-level ozone. This is to be achieved by limiting annual national emissions so that they do not exceed a ceiling laid down in the annex of the directive. Germany, for instance, is required to further reduce NO_x emissions in the year 2010 by 22 % compared to the year 2000. Even this emission reduction, according to the German Advisory Council on the Environment, will not be sufficient to meet the long-term goals of the NEC directive.

Even though the low level of ambition of the directive is criticized by many institutions, scenario calculations show that many countries will not even be able to comply with its soft ceilings. According to the European Topic Centre on Air and Climate Change, the main problems foreseen by countries relate to the emission of NO_x (ETC-ACC 2004). In the past few

decades, emissions of NO_x have generally decreased significantly, particularly due to measures taken regarding power plants and vehicles. In the recent past, however, the *rate* of reduction has decreased significantly, too.

The specific contribution of energy-related technologies to pollutant emission reductions is significant. Table 5.3 summarizes for some important air emissions the contribution of the energy sector to total European emissions. For instance, only 18 % of 1998 European NO_x emissions stemmed from the “energy industry” sector, while the dominant part was emitted by the transport sector. Of course, this does not imply that reducing NO_x in the power sector is of no importance. But it indicates the order of magnitude a possible reduction of impacts implies for the overall European emissions situation. It is remarkable that, for SO_2 , the energy industry causes almost two thirds of the European emissions, mainly due to coal power plants. It therefore seems reasonable to investigate options toward reducing these emissions, and to ask whether micro cogeneration may help lead to such a reduction path.

Table 5.3. Contribution of the energy sector to total pollutant emissions in EU15 (Source: EEA 2001, 2004)

%	1980	1990	1998	2001
CO_2		34.6	32.3	33.0
NO_x	25.1	21.3	18.0	
SO_2	57.3	61.6	65.0	
N_2O		4.3	3.8	
CO	1.0	0.9	1.0	
CH_4		0.2	0.4	
NM VOC	0.3	0.3	0.4	
NH_3	01	0.1	0.1	

It is common to all gas-based power plants that the emission of SO_2 is almost completely avoided. Also, in gas-based micro cogeneration and other power plant technologies, the contribution of ammonia to, e.g., acidification, is almost negligible. Therefore, of all exhaust emissions by micro cogeneration systems, NO_x is of particular ecological importance in the context of the NEC directive. Nitrogen oxides are formed during the combustion process in most of the micro cogeneration technologies and contribute to many environmental impact categories, such as acidification, human health impairment, and eutrophication. Furthermore, NO_x assists in the formation of Ozone and thereby contributes to summer smog and global warming; it also is a precursor material for the formation of small particles.

Whereas the total efficiencies of micro cogeneration technologies are similar, the various technologies differ considerably with respect to their emissions, particularly of NO_x . Reciprocating engines, which are based on discontinuous combustion at high temperatures, exhibit the highest emission factors. Stirling engines, due to their continuous combustion and the possibility of applying modern burner technology (such as flameless oxidation burners), lead to very low emission factors. This is also true for fuel cells, due to the electrochemical nature of their combustion, the comparatively low temperatures involved in the reforming reaction, and the requirement to clean up impurities such as sulfur and CO. The direct NO_x emission factors for the operation of micro cogeneration systems, as derived from analysis of existing technologies and field tests, are given in Table 5.1.

In the following, we will concentrate on acidification as an important impact category, mirroring particularly the differences with respect to NO_x emissions of micro cogeneration technologies and, when compared, for example, to coal power plants, SO_2 emissions.

In Germany, micro cogeneration systems have to be “state-of-the-art” in terms of pollutant emissions (see Sect. 8.1.7). This standard is regulated by the administrative instruction “TA-Luft”; the values of the TA Luft will be easily fulfilled by all micro cogeneration systems (Table 5.1). However, as pointed out in Sect. 8.1.7, in some other European regions, emission legislation is much stricter than in Germany with respect to small CHP.

Fig. 5.2 displays the results of the life cycle assessment of the micro cogeneration technologies for acidification. It shows that fuel cells offer great advantages with respect to environmental impacts that are caused by local pollutants, such as acidification (mainly due to NO_x and SO_2). This also holds for other impact categories not shown in the figure. Unlike engine CHP plants, fuel cells couple the advantages of reduced energy consumption with low direct emissions. The remaining acidifying emissions stem mainly from their natural gas operating supply and, to a much lower degree, from system production (for the PEMFC, 13 % of the total life-cycle emissions stem from system production, for the SOFC 9 %).

Similar advantages can be achieved by means of Stirling engines, which have very low direct emission factors as well, at least in the case of the innovative FLOX burner. For the small Stirling engine, we assumed that NO_x emissions of 80 mg/Nm^3 will be achieved in future systems from high-volume production.

Acidifying emissions from small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in large power plants.

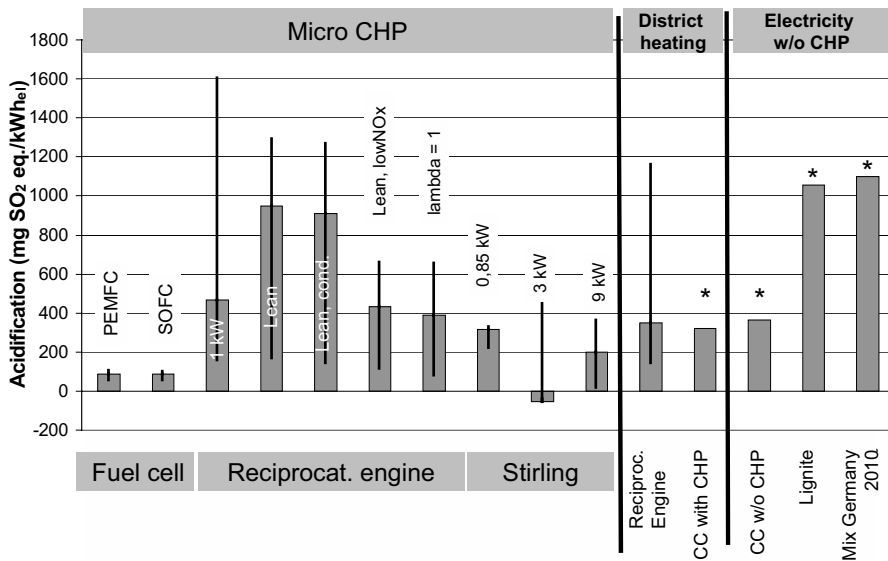


Fig. 5.2. Life cycle assessment of acidifying emissions (NO_x , SO_2 , NH_3) of micro cogeneration technologies compared to large CHP and conventional electricity production without CHP

5.2.3 Local Impacts from Air Pollutant Releases

When interpreting the LCA results for pollutant emissions, it is equally important to evaluate the impact of these emissions on the recipients side: how does the *local air quality* change due to the emissions? To address this question, the environmental relevance of the additional NO_x emissions of reciprocating engines will be assessed. For this purpose, a dispersion calculation for a virtual residential area was carried out, based on the software package AUSTAL 2000 (AUSTAL2000 2003). For this calculation, it was assumed that, in a residential area based on multi-family residences, one third of the houses would be equipped with a reciprocating engine. This corresponds to 100 systems in a 1 km^2 area. In addition, avoided air pollutant releases due to the substitution of an alternative gas heating system are accounted for.

With respect to technical parameters, we conservatively assumed 5000 hours of full load operation per year, an NO_x emission factor of 300 mg/Nm^3 (expressed as NO_2 , see Table 5.1), and a share of 10 % NO_2 of primary NO_x emissions. This latter assumption is of great importance, because NO_2 is of primary environmental concern. A site with flat topography with relatively critical weather conditions was selected: non-

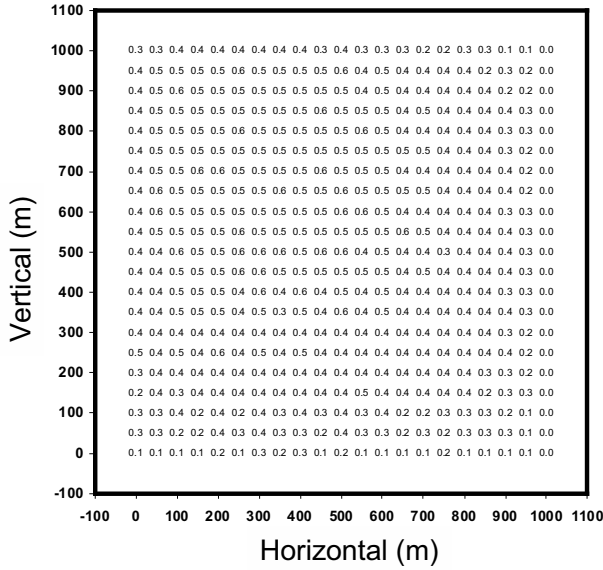


Fig. 5.3. Annual average concentration of NO₂ in ambient air (µg/m³) in a residential area due to installation of 100 reciprocating engines per km²

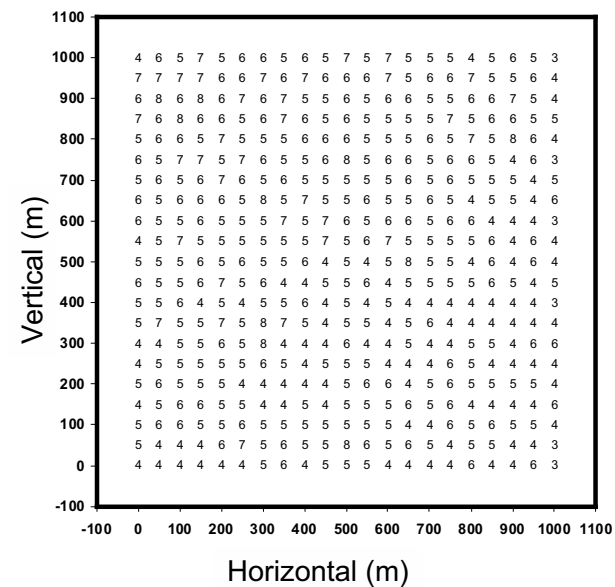


Fig. 5.4. Short-term concentrations of NO₂ in ambient air (µg/m³; indicating the concentration that is not exceeded in more than 18 hours/a) in a residential area due to installation of 100 reciprocating engines per km²

uniform wind distribution, large share of stable weather situations, and low wind speed that tend to lower the dispersion of pollutants. The surface texture corresponds to that of an urban area.

The results of this calculation are shown in Fig. 5.3 and Fig. 5.4. Fig. 5.3 depicts the additional annual average concentration of NO_2 in the residential area due to net emissions from reciprocating engines. The annual average of $0.6 \mu\text{g}/\text{m}^3$ can be compared to the permissible level for the annual average NO_2 concentration; the German limit being $40 \mu\text{g}/\text{m}^3$. The air concentration associated with the installation of the 100 units is very low – below a level of irrelevance, which is by German law defined as $1.2 \mu\text{g}/\text{m}^3$.

In addition, the maximum short term concentrations of NO_2 in air (i.e. not to be exceeded in more than 18 hours) are well below $7 \mu\text{g}/\text{m}^3$ (Fig. 5.4), compared to the allowable level which by German law is $200 \mu\text{g}/\text{m}^3$.

With respect to the impact on ambient air quality, reciprocating engines are not critical under the given circumstances. It has to be reiterated, however, that a flat topography was chosen for this analysis. Complex terrain (e.g. a narrow valley) might cause higher pollutant concentrations in certain places as calculated here.

From a national perspective, of course, every measure to reduce NO_x emissions is welcome. This is why, from our perspective, low- NO_x reciprocating engines should be further developed and marketed. The market leader, Senertec, for instance, offers a high- and a low- NO_x system. The specific capital cost of the latter is approximately 10 % higher. Thus, only 4 to 5 % of the Dachs systems sold belong to the low- NO_x class.

5.2.4 From Specific Impacts to Supply Objects

In the preceding sections, we have analyzed the environmental impacts per unit of electricity or heat produced, i.e. we have looked at the *specific* impacts. In addition, it is instructive to investigate the impacts per *supply object*, e.g. per single-family house, per apartment house, per hotel, etc. The question we want to answer here is: how much environmental impact reduction can be realized in concrete supply objects with concrete micro cogeneration systems? To answer this question, the specific environmental impacts (per kWh energy supplied) are multiplied by different full load hours, giving the annual environmental impacts.

This analysis involves a further step: we need to analyze the amount of electricity and heat produced by the CHP unit, depending on the object and the CHP system (size, partial load characteristics, etc.). This investigation was begun in Chap. 4 to determine the economic viability of micro cogeneration. We can build on the results of that chapter, i.e. the full load

hours, the share of own electricity consumption and grid electricity, the amount of heat produced in the peak boiler, etc. As the technologies were defined identically, we can directly use those results for further calculations.

It is important to note that the calculations in Chap. 4 are based on real available or planned systems. For instance, the calculations for a single-family house utilize an 850 Watt Stirling engine (like the WhisperTech), a 1 kW solid oxide fuel cell (like the Sulzer Hexis system) or a 1 kW reciprocating engine (Honda) (Table 5.4). The differing efficiencies and power-to-heat ratios also imply different full load hours.

We have chosen this approach because it provides additional information; we can not only estimate the impact reduction per supply object, but also how well a particular system fits the need of a supply object.

Table 5.4. Investigated technologies for the LCA of supply objects

	Reciprocating engine	Stirling engine	Fuel cell	District heating
Technologies				
Single-family (low)	1 kW	850 Watt	1 kW SOFC	20 kW rec.eng. w/ 17.8 % heat loss
Multi-family (average)	5.5 kW	3 and 9 kW	4.7 kW	50 kW rec. eng. w/ 2.4 % heat loss
Hotel	5.5 kW	3 and 9 kW	4.7 kW	
Full load hours (h/a)				
Single-family (low)	3373	1940	4786	4800
Multi-family (average)	5526-5639	5509-4160 ^a	6432	6456
Hotel	5555-5730	5505-3939 ^a	7015	-
Share of electricity produced in CHP (%)				
Single-family (low)	29	13	41	39
Multi-family (average)	24	13-31 ^a	24	17
Hotel	26	14-31 ^a	24	17
Share of heat produced in CHP (%)				
Single-family (low)	95	100	68	62
Multi-family (average)	61-65	65-93 ^a	39	30
Hotel	65-68	68-92 ^a	45	-

^a First value: small Stirling, second value: large Stirling

Beside the LCA of the specific impacts (per kWh) of each CHP unit, which were derived in the preceding sections, we need to model the energy flows of our supply objects (Fig. 5.5). Therefore, for each object, we need to include the following information:

- The net electricity demand of the supply object. The supply object may require additional electricity, and the CHP unit may also feed electricity into the grid. We assume that the substituted electricity and the electricity fed into the grid have the same “quality”. This is, to a certain extent, a simplification because micro cogeneration systems are very often thermally led; the electricity production of micro cogeneration units is therefore at maximum in periods of high space-heating demand, which are often also times of high electricity demand. Therefore, micro cogeneration might avoid the need for electricity production from environmentally more problematic peak load power plants (see Sect. 5.3.2).

Assuming the identical quality of grid electricity bought by the supply object and of electricity fed into the grid, we therefore calculate a net electricity demand. It can be either positive, if less electricity is sold to the grid than bought, or negative, if more electricity is fed into the grid than bought.

- The CHP unit does not cover the full thermal load of the object. Therefore, peak load demand is considered to be covered by a modern gas condensing boiler.

This supply combination of micro cogeneration, grid electricity, and condensing boiler can then be compared to the reference, which assumes 100 % coverage of electricity demand via the German electricity mix from the grid and heat demand from a condensing boiler. Again, our reference time is 2010. The functional unit for this type of analysis is the supply of an object with heat and electricity for one year.

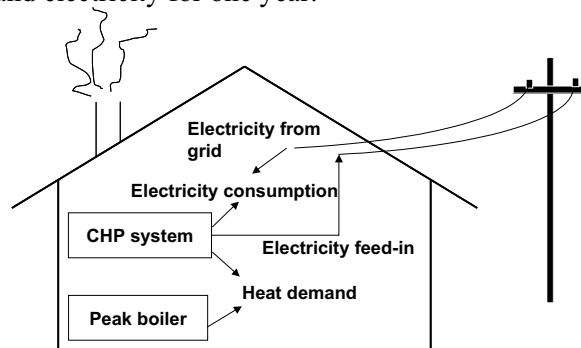


Fig. 5.5. Analysis of supply objects

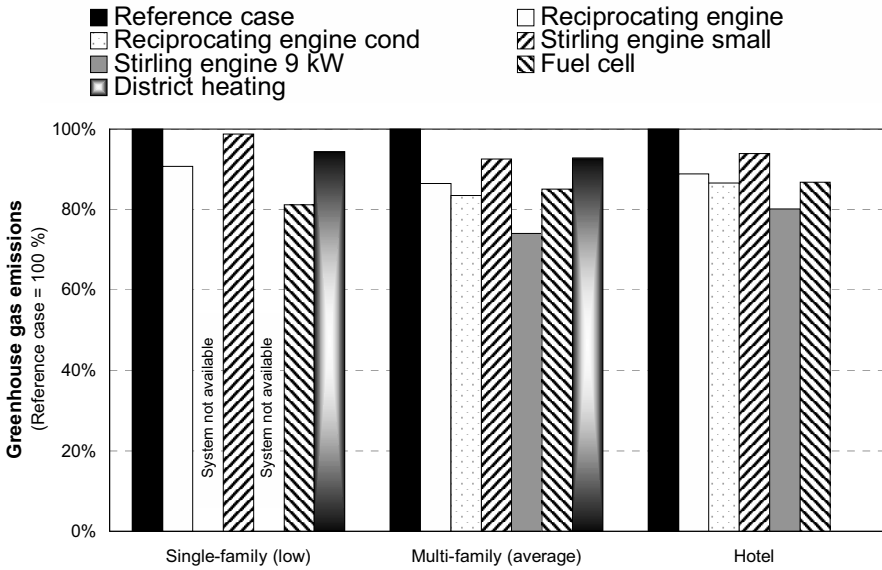


Fig. 5.6. Greenhouse gas emissions of different supply objects

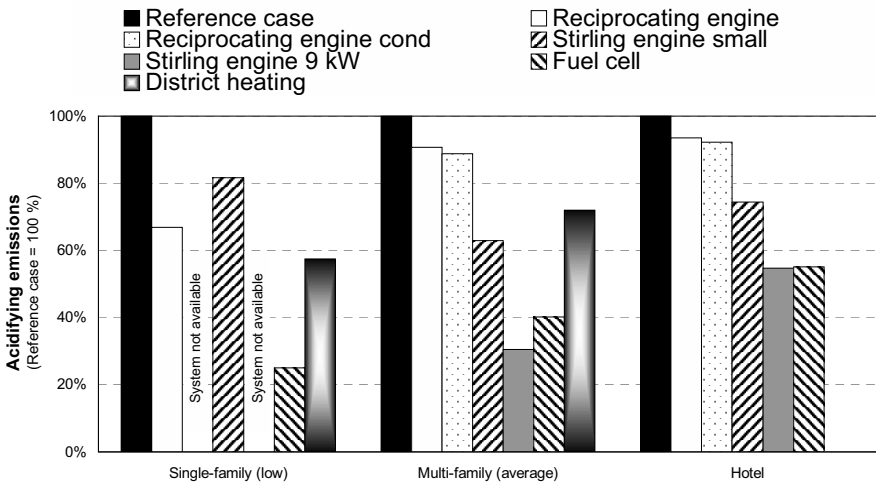


Fig. 5.7. Acidifying emissions of different supply objects

Selected supply objects (see Chap. 4): single-family house with low average heat demand, multi-family house with average heat demand, and small hotel; functional unit: supply of an object with heat and electricity for one year; reference case: grid electricity and gas condensing boiler

The results of this analysis for the impact categories GHGs and acidification are shown in Fig. 5.6. In all cases, the default technology assumptions listed in Table 5.1 are used for the assessment. Several important conclusions can be drawn based on this analysis:

- Unsurprisingly, the advantages of the individual technologies, as assessed in Chap. 5.2, are mirrored in this analysis. This means that CHP technologies offer climate advantages, the fuel cell offers additional acidification advantages, and so on.
- On the other hand, in an economically optimized system configuration, the CHP units cover only between 10 and 40 % of the electricity demand, and between 30 and 100 % of the heat. This implies that the rest has to be supplied by the electricity mix and the conventional heat system. Therefore, the GHG emission reduction of around 20 to 30 % in Fig. 5.1, for instance, is reduced to between 10 and 20 % when regarded per object supplied, due to the constant base demand of peak boiler heat and electricity.
- From this perspective, the fuel cell can increase its competitive advantage particularly in the case of the *single-family house*. The reason is that these systems are limited by the prevailing heat demand. Because the fuel cell has a higher power-to-heat ratio, it produces more electricity for a given heat demand and can thus substitute higher amounts of grid electricity. The district heating system, in contrast, has rather high losses of 17.8 % in the case of single-family houses (and concomitant low heat demand density).
- In the *multi-family house* connected to the district heating grid, in contrast, the heat losses drop to 2.4 %; thus, the difference between district heating and micro cogeneration shrinks as well. In addition, however, district heating has a lower share of the overall heat supply.

In absolute terms, GHG reductions from one ton per year (single-family house) to 11 tons per year (hotel) can be achieved by operating micro cogeneration compared to the electricity mix. Carrying out the same analysis for gas combined cycle plants as suppliers of grid electricity reduces these advantages.

5.2.5 From Gas to Renewables: Other Micro Cogeneration Fuels

In the preceding section, only natural gas as a fuel was investigated, because we believe this will be an important fuel for many European applications (see Chap. 9).

However, particularly for areas outside of larger population agglomerations, other fuels will be of high importance. Fuel oil can be more easily distributed in rural areas than gas. The picture changes further when we move to other regions worldwide. In Japan, for instance, liquefied petroleum or natural gas (LPG and LNG), fuel-oil, or other fuels will be important (see Chap. 13). Also, renewable fuels can, and in the mid-term will, also be used for micro cogeneration applications.

It is not the place here to carry out a number of further LCAs. However, because of the relevance of fuel oil, it was included in a sensitivity analysis (Fig. 5.8). A reciprocating engine operated with fuel oil, on the one hand, combusts a fuel with higher carbon content and, hence, emits more CO₂ per MJ fuel than gas. On the other hand, the efficiency of such a unit is slightly higher (by some 2 to 3 % points; see Table 5.1) than that of a gas unit. In addition, such units will not be replacing gas condensing boilers, but rather modern fuel oil heating systems.

In Fig. 5.8, we compare a 5.5 kW gas- or fuel-oil operated engine (corresponding to the Senertec Dachs) with the large non-CHP power plants from Chap. 5.2.1 ff. We observe that in terms of GHG mitigation, the oil reciprocating engine achieves almost the same level as the gas engine for the reasons given above. However, the acidifying emissions are substantially higher in the case of the oil CHP unit. This is primarily due to the much higher NO_x emissions of the fuel-oil CHP unit.

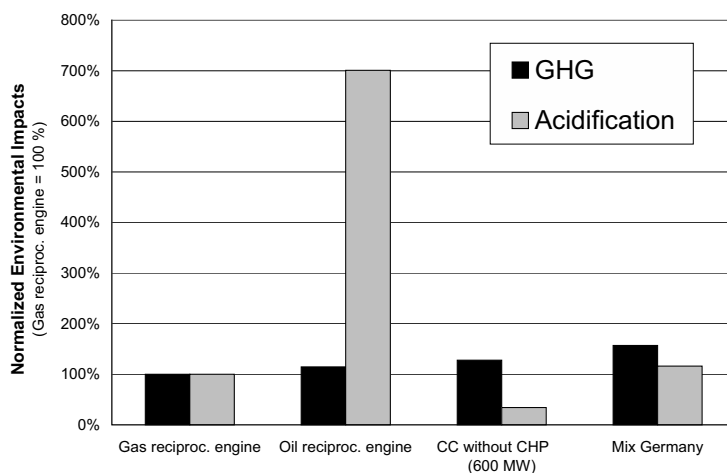


Fig. 5.8. Selected life cycle impacts of micro cogeneration technologies with gas and fuel oil compared to a combined cycle (CC) plant without CHP and conventional electricity production in the year 2010

Functional unit 1 kWh electricity at low voltage level; co-produced heat is credited with a gas condensing boiler (gas reciproc. engine) and an oil condensing boiler (oil reciproc. engine)

When using *renewable fuels*, e.g. biogas or wood pellets, the overall GHG emissions for micro cogeneration systems will be drastically reduced. Even for rapeseed oil, the LCA will show significantly lower overall GHG emissions, despite its production requiring fossil fuel inputs and leading to further greenhouse gases due to the emission of N_2O from the agricultural system (Gärtner and Reinhardt 2003). This positive GHG balance is, however, a general characteristic of most renewable energy systems (Pehnt 2005) and not only of renewable micro cogeneration, implying that also on the side of centralized production of electricity, large CHP, or decentralized heat production without cogeneration, renewable, and thus virtually GHG-free, systems could be identified. In other words: when we discuss renewable fuels, the GHG (and energy) assessment per kWh final energy delivered will be excellent for almost all conversion systems, regardless whether they are small or large. In the context of that discussion, aspects such as technical maturity, logistical feasibility and cost are very important to keep in mind (see Sect. 9.4).

5.3 Beyond the Single Micro Cogeneration Unit

So far, we have discussed environmental impacts arising from installation of single micro cogeneration power plants. But there are also impacts on a more abstract system level, which are either caused by the number of systems, or which are of a more indirect nature. These impacts shall be qualitatively discussed in the subsequent chapters.

5.3.1 Avoided Grid Losses

Micro cogeneration units produce electricity in direct proximity to the customer. Either the produced electricity is directly used within the object, or the CHP electricity is fed into the low-voltage grid, but typically not transformed to the medium-voltage grid.

Grid losses are reduced not only by the reduced haul length, but also the lower net currents required and, thereby, the lower Ohmic losses and lower resistance of conductors and transformers, due to the lower temperatures of these devices. However, it is very difficult to determine actually avoided grid losses, because they “depend not only on the grid load displaced but also on the time, weather, load conditions, loadshapes, and – especially – physical placement in the grid” (Lovins et al. 2002). For example, on the low-voltage level, electricity losses in Europe range from 6.1 % in Germany and 9.6 % in France to 24.2 % in Croatia (Pehnt 2002;

Frischknecht and Emmenegger 2003). For the United States, Lovins et al. 2002 report distribution losses ranging between 3 and 13 %.

The possibility of avoiding grid losses also depends on the capacity of a system to reduce reactive power consumption and on the load following capabilities of the system. If, for instance, an electricity-led CHP device does not react instantaneously to changes in the electricity demand of the household, the excess electricity is fed into the grid. For thermally-led micro cogeneration units, in periods of low general consumption, grid losses might increase, whereas in periods of high consumption, the losses might decrease (Lehmann et al. 2003). Distributed generation might also enhance grid losses in cases where generation is located at the end of a network or connected with long feeding cables.

Arndt et al. (2004) calculate the impact of micro cogeneration (fuel cell) systems for a given Bavarian low-voltage grid and determine a reduction of some 0.26 %-points. Converted to, for instance, GHG emissions, this would translate to only 2 g CO₂ equivalents/kWh_{el} for the German electricity mix. From an environmental point of view, this is only of minor importance. In terms of economic viability, however, the congestion relief of the grid can be of importance, especially in cases where adding grid capacity can be deferred or even avoided (see Chap. 9).

5.3.2 Connecting Micro Cogeneration to Create Virtual Power Plants

Starting from the conventional micro cogeneration application, it is often argued that connecting many micro cogeneration units to create a “Virtual Power Plant” would offer additional economic advantages. But the virtual power plant application could also have additional environmental benefits:

- **Avoiding more “dirty” marginal power plants.** When one central operator co-ordinates the operation of micro cogeneration units, one objective could be to minimize the demand for peak load electricity or even to use the devices for regulating energy for other fluctuating energy sources, such as renewable energy carriers. Regulating energy is not only more expensive but also, in many cases (exception: hydropower from reservoirs), more environmentally intensive with respect to GHG emissions and other impacts. In Germany, peak load power plants are particularly old fuel-oil and gas power plants. Even in cases where hydropower is used for peak load purposes, peak shaving would set free hydropower capacity for other purposes, such as integration of renewables.

- **Enhanced full load hours of CHP systems.** A higher load factor due to more optimized system operation could lead to more CHP electricity and heat generation, thereby substituting for more conventionally supplied energy. Also, heat losses due to stand-by operation of CHP plants could be reduced in this way.
- **Enhanced acceptance by utilities of fluctuating energy systems.** A more “company-psychological” factor is that, by employing virtual power plant communication, municipal utilities will more easily be prepared to accept fluctuating energy feed-ins, such as wind or solar power, because they have the possibility to partially balance these fluctuating energy contributions by controlling the electricity production of their individual systems. This aspect, however, is more focused on renewable-based virtual power plants and is less relevant for micro cogeneration.

5.3.3 Indirect Ecological Impacts through User Behavior

Ecological impacts of technologies are not determined solely by their technological characteristics nor by their being embedded in technological and economical systems. New technological options may stimulate new behaviors, habits, and routines that counteract, or reinforce, the environmental effects of the technology (see also Chap. 6).

It is difficult to predict the indirect effects of micro cogeneration, as no systematic research on its users has been done so far. However, we can make inferences from experience with other energy-related technologies. Among them are energy-efficient household appliances, efficient conversion technologies, and the use of renewable energy sources.

In efficient appliances and conversion technologies, a *rebound effect* is often found (Gottron 2001; Menges 2003). This means that energy savings achieved by more efficient technologies are at least partly compensated, and sometimes overcompensated, by an increase in energy demand. The rebound effect can be traced to different causes.

First, new technologies may stimulate energy demand by offering new comfort features. It is a well-known effect, to give an example, that the switch from single coal or wood stoves to central heating in residential buildings leads to increases in energy consumption of up to one third, even though central heating is more efficient. The reason is that, given the possibility to heat all rooms easily and comfortably, users increase the number of heated rooms as well as the average temperature (Kleemann et al. 2000, p.13; Wilhite and Norgard 2003).

Secondly, energy-efficient technologies reduce expenditure for energy services and, therefore, set free disposable income, which may in turn increase the expenditure on energy-consuming appliances (direct rebound effect) or on consumer goods which need energy for their production (indirect rebound effect).

Thirdly, psychological research on environmental consciousness and action has shown that environmental behavior is selective, and people draw up a “subjective ecobalance” by offsetting certain symbolic types of environmental action against behavior in other areas. Performing a specific “environmentally friendly” behavior salves the conscience and legitimizes abandoning environmental considerations elsewhere. Possessing an energy-efficient technology can therefore provide an excuse for using it excessively or using other energy-consuming equipment (Diekmann and Preisendörfer 1992 and 1998, Bilharz 2003).

Similar considerations apply to the use of *renewables*: the sensation that energy is, economically and ecologically, “for free”, invites liberal use.

Finally, if a resource is used less due to more efficient applications, the resource price declines, thereby stimulating demand for the resource again (market effect).

However, new eco-effective technologies may also stimulate environmental consciousness. This is particularly true for energy conversion technologies. The installation and monitoring of a new conversion system implies an involvement with topics of energy conversion and use. In some cases, detailed feedback on performance is provided that can be compared with consumption patterns. Research shows that timely and detailed feedback on both electricity and heat consumption can greatly reduce them (Jensen 2003; McCalley 2003). Information on production, especially when combined with information on consumption, is likely to have a similar effect.

Whether a new technology stimulates environmentally beneficial or unfavorable behavioral changes or not, depends heavily on the respective technology and on the context. Economic incentives for increased consumption are only present when the new technology indeed “pays off” and financial savings are not overcompensated for by rising energy prices. Direct rebound effects depend on whether increased appliance use or number of appliances indeed promises improved comfort – room temperature, for example, will not be raised indefinitely. Psychological offsetting of environmental benefits and damage depends on many aspects: how strongly is ecologically sound behavior perceived as a social or personal norm? Are we dealing with a conscious decision or habitual behavior? How much does the person know about the actual environmental effects of various behaviors? Whether information and

feedback can help to change consumption patterns depends on subjective motivation and the actual amount, detail, and form of information provided.

Various technologies and contexts lead to an array of different empirical findings. Van Elburg (2001) finds a strong rebound effect in cooling appliances and compact fluorescent lamps. Cooling appliances are replaced by bigger ones, and lamps are increasingly used to light previously unlit areas – for example, the garden. This is for several reasons. Apparently, both types of appliances provide noticeable financial savings that can be invested in additional appliances. Furthermore, bigger fridges allow comfort gains in terms of better planning of household purchases and supply, and illuminating the garden satisfies aesthetic and status needs. Nadel (2003), in contrast, reports very weak rebound effects in appliances, with the exception of air conditioning and compact fluorescent lamps. Unfortunately, no more details are given. Henderson et al. (2003) report that rebound effects in heat energy consumption occur after the installation of insulation especially in households with low prior energy consumption and in houses which had greater heat loss. Similar effects are found by Genennig and Hoffmann (1996) and by Haas et al. (1999) for home electricity generation via photovoltaics: electricity consumption rises in households with low prior consumption and decreases in households with high prior consumption. Apparently, the “free” energy is used to raise the comfort level of users who were previously deprived of such comfort. In contrast, Haas and Biermayr (2001) find no difference in electricity consumption between households using renewable energies and conventional households. A temporal perspective on *changes* in consumption, however, is lacking here. What is interesting is the fact that most renewable energy users subjectively *perceive* themselves as energy conscious and economical (Karsten 1998; Haas et al. 2001). Another interesting effect is observed by Haas et al. (1999) and Reif (2000): photovoltaics users are willing to adapt their temporal consumption patterns to the production patterns of their panels, in order to maximize self-reliance. In Reif (2000) this is supported by financial incentives.

What can be inferred from these findings for micro cogeneration?

1. Micro cogeneration is targeted at home owners who, in Germany, form a relatively wealthy section of the population. It is safe to assume that the comfort levels of their dwellings are already high. Therefore, a significant increase of energy consumption is improbable.
2. A positive effect of feedback and increased involvement with energy topics is possible, but depends highly on the specific form, timing, and

- amount of detail of feedback, and on the presence of other incentives – e.g. price incentives, importance of independence, or ecological motives. It seems advisable to provide information both on production and consumption patterns to allow users to compare and match them.
3. Similar to photovoltaics, there is potential for adapting temporal consumption patterns. This opens up interesting possibilities for load management.
 4. One potential rebound effect may result from the German Energy Savings Decree (*Energieeinsparverordnung*, EnEV). The decree sets a maximum level for the overall energy demand in new buildings. Building owners who install a micro cogeneration plant are permitted to apply less stringent heat insulation measures. However, poor insulation of buildings has very long-term implications on energy demand, while a micro cogeneration plant that has reached its technical life span may be replaced by a conventional boiler, increasing the energy demand of the building.
 5. Finally, it is difficult to predict to what extent micro cogeneration possession may be used as a justification for otherwise ecologically unsustainable consumption patterns. This depends, among other things, on the relevance of ecological norms to the user, on the consciousness of behaviors, on the degree to which micro cogeneration possession is perceived as ecologically relevant, and on knowledge of its effects. This is a question that needs to be empirically explored.

5.4 Conclusions

Most micro cogeneration systems are superior, as far as the reduction of GHG emissions is concerned, not only to average electricity and heat supply, but also to efficient and state-of-the art separate production of electricity in gas power plants and heat in condensing boilers. This claim is the result of our Life Cycle Assessment on the technology level. It is true, despite the strong dependence of the results on the electrical and thermal efficiency of micro cogeneration technologies and further parameters such as methane emissions from reciprocating engines. Effectively, at an electrical capacity of up to five orders of magnitude smaller than large gas combined-cycle power plants, lower GHG emission levels can be achieved. The GHG advantages of micro cogeneration plants are comparable to district heating with CHP.

The performance of micro cogeneration technologies with respect to climate and resource protection depends mainly on the total conversion

efficiency (including the thermal output of the system) that can be achieved. In some cases, an unfavorable heat integration of micro cogeneration systems may lead to operation at the lower end of the assumed bandwidths of total efficiency. In such cases, CHP systems come rather close to electricity production in modern combined cycle plants without CHP. The optimization of micro cogeneration implementation thus involves careful integration into the supply object. Generally, the systems should not be oversized, to ensure that the full amount of heat is actually used in the system.

Under the assumption that gas-condensing boilers are the competing heat-supply technology, all technologies are within a very narrow range, with the exception of the small Stirling engine, with its lower electrical and total efficiency.

Looking at the GHG reduction potential on the level of a supply object (e.g. a single-family or multi-family house), the mitigation potential is somewhat lower, because the micro cogeneration systems do not supply the whole energy demand. Rather, additional electricity from the grid and heat from a peak boiler have to be taken into consideration. Here, fuel cells offer the advantage of a higher power-to-heat ratio, implying that, for a given heat demand, more electricity can be generated that displaces conventionally produced electricity.

Environmental impacts other than those related to climate and resource protection relate more specifically to technology. Whereas for fuel cells and Stirling engines (as long as these use innovative flameless burner technologies) emissions of air pollutants are extremely low, reciprocating engines emit more significant amounts of NO_x , CO, and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics, age and maintenance of the systems. Thus, larger bandwidths characterize this system. As a consequence, acidifying emissions of small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in the latter.

In addition to investigating the emissions side, analysis of the immissions situation of a residential area supplied by reciprocating engines was carried out. The analysis shows that for selected, rather unfavorable, meteorological conditions, with a flat topography and urban housing structure, the additional immission of NO_x due to the engines is below the value of significance according to German legislation, and does not create severe additional environmental impacts.

The emissions reduction and resource protection potential of micro cogeneration could partially be offset by a “rebound effect”, implying that energy savings achieved by a more efficient technology are at least partly

compensated, and sometimes overcompensated, for by an increase in energy demand. On the other hand, use of innovative energy systems in the household may rather sensitize its users regarding energy consumption and stimulate more energy conscious behavior.

Which of either of these effects prevails is an empirical question. We suspect that increasing comfort will not occur to a relevant degree, because micro cogeneration is targeted at a part of the population which has already reached satisfactory comfort levels. The effects of additional income and psychological offsetting cannot be exactly determined. The former depends on to what extent micro cogeneration indeed produces financial savings. The latter is influenced by many factors, including environmental consciousness and knowledge about the environmental impact of various behaviors.

A positive effect of feedback and increased involvement with energy topics is possible, both concerning total energy consumption and temporal adaptation of electricity use. The exact effect depends highly on the specific form, timing and the level of detail of feedback, and on the presence of other incentives.

When interpreting the overall environmental achievements of micro cogeneration, it has to be kept in mind that, as long as the fuels for micro cogeneration units are based on fossil resources, greenhouse gases are emitted and finite energy resources used. Therefore it is necessary to embed the use of micro cogeneration units into a strategy of renewable energy carriers, energy efficiency, and energy saving.